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Notes

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Description of a new beaked whale echolocation pulse type in the California Current

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Beaked whales (family Ziphiidae) present unique challenges to visual monitoring and mitigation efforts because they have long foraging dives, short surface times, and have inconspicuous surface behavior (Barlow *et al.* 2005). For Cuvier's beaked whale, *Ziphius cavirostris*, one of the better studied beaked whales, the mean dive and surface times are 58 min and 1.9 min, respectively (Tyack *et al.* 2006, Schorr *et al.* 2014). Fortunately, many beaked whales produce species-specific frequency modulated (FM) pulses, or upswept echolocation clicks (Baumann-Pickering *et al.* 2013, 2014), and have stereotypic vocalizing behavior, making them amenable to passive acoustic monitoring.

Eight species of beaked whale are thought to inhabit the California Current off the U.S. West Coast; six are in the genus *Mesoplodon*. Species-specific FM pulses have been characterized for only four species: Cuvier's, Baird's (*Berardius bairdii*), Blainville's (*M. densirostris*), and Stejneger's (*M. stejnegeri*) beaked whales (Dawson *et al.* 1998, Madsen *et al.* 2005, Zimmer *et al.* 2005, Johnson *et al.* 2006, Baumann-Pickering

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et al. 2013, 2014, Stimpert *et al.* 2014, Keating *et al.* 2016). FM pulses attributed to these species differ in several acoustic features, including: peak frequency, center frequency, spectral notch frequency (if present), −3/−10 dB bandwidth, duration, and interpulse interval (IPI).

The four uncharacterized species are Hubb's (*M. carlhubbsi*), Perrin's (*M. perrini*), pygmy (*M. peruvianus*), and gingko-toothed (*M. gingkodens*) beaked whales, the latter two of which occur mainly in more tropical and subtropical waters and are thus rare off the U.S. West Coast (MacLeod *et al.* 2005, Baumann-Pickering *et al.* 2013). However, several FM pulses have been described and are thought to belong to some of these uncharacterized species. Baumann-Pickering *et al.* (2013, 2014) labeled three pulse types BW40, BW43, and BW70, based on their dominant spectral content, and suggested they might be associated with Hubb's, Perrin's, and pygmy beaked whales, respectively. Both BW43 and BW70 have been recorded within the presumed geographic range of the suggested species (Baumann-Pickering *et al.* 2013). FM pulse BW40, however, has been documented mostly in the Southern California Bight, but also off Point Sur, California (36°17.9′N, 122°23.6′W) and in the Pacific Islands as far southeast as the Wake Atoll (19°13.0′N, 166°41.0′E) (Baumann-Pickering *et al.* 2013, 2014). Hubb's beaked whale is distributed throughout the California Current ecosystem but does not commonly occur below 30°N (Mead *et al.* 1982, MacLeod *et al.* 2005, Baumann-Pickering *et al.* 2014). Additionally, Hubb's beaked whale is the only *Mesoplodon* species other than Stejneger's beaked whale that is thought to occur in the northern California Current (Mead *et al.* 1982, MacLeod *et al.* 2005). The BW40 pulse is recorded only in the southern region of Hubb's beaked whale distribution and near tropical and subtropical islands that are clearly outside the expected range of this species (MacLeod *et al.* 2005, Baumann-Pickering *et al.* 2014). If not Hubb's beaked whale it is possible that BW40 is a variant of a different beaked whale pulse or from a species with the same geographic range.

Here we describe a new frequency-modulated echolocation pulse that is similar to, but distinct from, other beaked whale species in the California Current. It possess upper and lower peak frequencies and a distinctive valley (or notch) frequency[2] further described below. Acoustic recordings used for our analyses were collected on the 2016 Passive Acoustic Survey of Cetacean Abundance Levels (PASCAL) cruise, which was conducted on the NOAA R/V *Bell M. Shimada*. This was a dedicated beaked whale acoustic survey off California, Oregon, and Washington, typically 50–300 nmi from the coast. Drifting Acoustic Spar Buoy Recorders (DASBR, Griffiths and Barlow 2015, 2016) were deployed from the ship in a systematic distribution to broadly cover our study region and allowed to drift for days to weeks before retrieval. DASBRs are autonomous, free-floating acoustic recorders, capable of surveying waters deeper than 1,000 m and can be left at sea for several months.

[2] Other authors have used the term "spectral notch" (*e.g.*, Soldevilla *et al.* 2008), but we use the term "valley," which is more analogous as the opposite of a "peak" frequency.

The DASBRs were configured with a vertical two-hydrophone array ~100 m below the surface and 10 m separation between hydrophones.

Three types of ultrasonic recorder were used: Wildlife Acoustics' SM2 +Bat and SM3M, and the Ocean Instruments' Soundtrap 4300[3] (Table 1; Barlow and Moore 2017). HTI-96-Min and HTI-92-WB hydrophones were used on all deployments, with sensitivities ranging between −182 and −154 dB re: 1V/1uPa. Additional information regarding the gain and high pass filter settings used for each deployment is outlined in Barlow and Moore (2017). There were a total of 30 DASBR deployments, or drifts, using 19 different units. Initial deployment location selected in a systematic distribution to broadly cover our study region (Fig. 1). Sampled areas were dependent on deployment location, current, and weather patterns with each drift lasting 1.5–23.4 d. All DASBR units were successfully retrieved, although one of the 30 (Drift #14, deployed off the coast of Washington) malfunctioned and thus did not collect data. Duty cycles were selected to match the capabilities and expected drift durations for each instrument. All DASBRs recorded 2 min WAV files, but different types of recorders used different duty cycles (Table 1). All files record during a drift were included in this analysis, using the presence of characteristic upswept pulse types within a 2 min time period to standardize among instruments.

All DASBR recordings were processed in PAMGuard's Click Detector module (ver. 1.15.03, Gillespie *et al.* 2008). Echolocation-type signals were automatically identified with an energy detector and classified based on peak frequencies and presence of a frequency upsweep (Keating and Barlow 2013). Output from PAMGuard was first independently reviewed by two of the authors (JLK and ETG) to verify instances of three or more FM pulses within each 2 min sample; no species classifications were assigned at this time. These events were then reviewed by three of the authors (ETG, JLK, and JB) following a dichotomous protocol developed during this analysis based on pulse descriptions outlined in Baumann-Pickering *et al.* (2013). Using the species-specific FM pulse characteristics, each event was classified as either a known species of beaked whale (*e.g.*, Cuvier's beaked whale), a characteristic beaked whale pulse type (*e.g.*, BW43), an unidentified beaked whale pulse (BWunid), or a potentially confounding species (*e.g.*, Risso's dolphin, *Grampus griseus*). Prior to this classification exercise, we expanded the Baumann-Pickering *et al.* (2013) list of beaked whale pulse types to include characteristic pulse types that we identified in preliminary review of our data (including the pulse described here). All pulse types presumed to be *Mesoplodon* species were classified without knowledge of recording location by two of the authors (ETG and JB). Four major criteria (Fig. 2) were considered when discriminating among potential beaked whale FM pulses: (1) FM pulse spectral features averaged over a full event and the highest amplitude pulses; (2) appearance of high amplitude pulse upsweeps in the Wigner plot; (3) absence/presence of

[3] No mention of products in this document indicates endorsement by the U.S. Government.

Table 1. Description of the three different DASBR units deployed during PASCAL, and the duty cycle employed. All sampling was based on 2 min WAV files.

Recorder	Sample rate	Number of units	Duty cycle
Wildlife Acoustics M2 +Bat	192 kHz	4	2 min on/4 min off
Wildlife Acoustics SM3M	256 kHz	4	58 min on/2 min off [a]
Soundtrap ST4300	288 kHz	11	2 min on/10 min off

[a]The SM3M recorded for 56 continuous minutes to 2 min sound files every hour. To obtain cleaner ocean noise measurements, SM3M DASBRs recorded a 2 min sound file at a lower sampling rate, 96 kHz, every hour, followed by a 2 min gap in recording.

other pulse types (*e.g.*, dolphin echolocation, confounding species); and (4) pulse-train bearing angles. Vertical bearing angles generated by PAMGuard (based on the time-difference of arrival of the same pulse between the two hydrophones) provided information about the location of the sound source relative to the hydrophone array. Pulse events with a bearing angle greater than 90° (*i.e.*, below the array) were used to identify deep sound sources (Griffiths and Barlow 2015).

To extract measures from these pulses, custom R code was used to format each waveform from the PAMGuard binaries for R (https://github.com/TaikiSan21/PamBinaries). The R packages *signal* (signal developers 2013), *seewave*, and *tuneR*, (ver. 3.4.1, in RStudio ver. 1.1.383; RStudio Team 2015; Sueur *et al.* 2008, Ligges *et al.* 2016) were used to further process the waveforms of each pulse. Frequency response curves for the HTI-92-WB (low-noise; 56–165 dB SPL) and HTI-96-Min (standard; 78–165 dB SPL) were applied to pulse waveforms in R respective of which hydrophone the pulse was recorded (Wildlife Acoustics 2017). To reduce the presence of off-axis signals only pulses 20 dB above the median Teager-Kaiser (TK) energy noise floor, based on a 256-FFT spectrogram, were included. Feature measurements included upper and lower peak frequencies, valley frequency, center frequency, −3/−10 dB bandwidths, resonant quality factor Q, and duration (TK energy 100 times greater than the noise floor at the 40th percentile, Soldevilla *et al.* 2008). Custom R scripts were also used to extract the IPI and declination angle for each pulse from the PAMGuard binary metadata. Bottom depths for each event were obtained using the R package *marmap* (Pante and Simon-Bouhet 2013).

A spectral valley indicates the absence of power within a pulse bandwidth, and the valley frequency is the point of lowest power in that drop. Soldevilla *et al.* (2008) concluded that the presence of peak/valley frequency banding patterns is useful for Risso's (*Grampus griseus*) and Pacific white-sided dolphin (*Lagenorhynchus obliquidens*) species discrimination. This is true in beaked whales as well. The Cuvier's beaked

Table 2. Descriptive statistics for the BW37V click type. All frequency measurements presented in kHz. Outliers were removed from the final duration summary (longer than 500 µs). All pulses were included to measure the interpulse interval (IPI) and the pulse declination angle, rather than just the pulses 20 dB above the noise level, as was necessary for the spectral measurements. Outliers were removed from the final IPI summary (longer than 500 ms). The resonant quality factor, Q, is an estimate of the frequency pureness of a time wave measured by center frequency/bandwidth.

		n	Mean	SD	Median	Minimum	Maximum	SE
	Duration (µs)	216	213.11	87.69	219.05	43.03	488.94	5.97
	Valley frequency	238	37.10	2.65	37.52	25.21	47.93	0.17
	IPI (ms)	1,152	146.53	58.85	139.06	25.11	496.67	1.73
	Declination angle (°)	1,369	115.61	15.07	116.16	56.00	140.78	0.41
Overall −10 dB bandwidth	Q factor	238	3.13	1.92	2.42	1.03	11.65	0.12
	Bandwidth	238	19.32	10.44	18.89	2.80	49.42	0.68
	Frequency minima	238	36.81	4.95	38.19	26.38	57.35	0.32
	Frequency maxima	238	56.13	14.03	56.35	31.33	96.99	0.91
	Center frequency	238	46.47	9.14	47.71	29.54	77.16	0.59
Upper peak −3 dB bandwidth	Q factor	238	6.01	3.16	5.34	1.66	25.07	0.21
	Peak frequency	238	47.85	7.30	46.90	29.53	96.23	0.47
	Frequency minima	238	42.06	3.83	42.22	28.37	60.97	0.25
	Frequency maxima	238	52.30	7.97	51.79	30.90	99.73	0.52
	Bandwidth	238	10.24	6.91	8.84	1.30	56.66	0.45
Lower peak −3 dB bandwidth	Q factor	238	10.01	4.68	9.95	0.90	25.68	0.30
	Peak frequency	238	36.11	5.67	34.78	22.27	53.94	0.37
	Frequency minima	238	34.39	5.04	33.30	21.27	49.82	0.33
	Frequency maxima	238	39.89	9.63	36.59	22.80	86.12	0.62
	Bandwidth	238	5.50	5.72	3.42	1.28	45.79	0.37

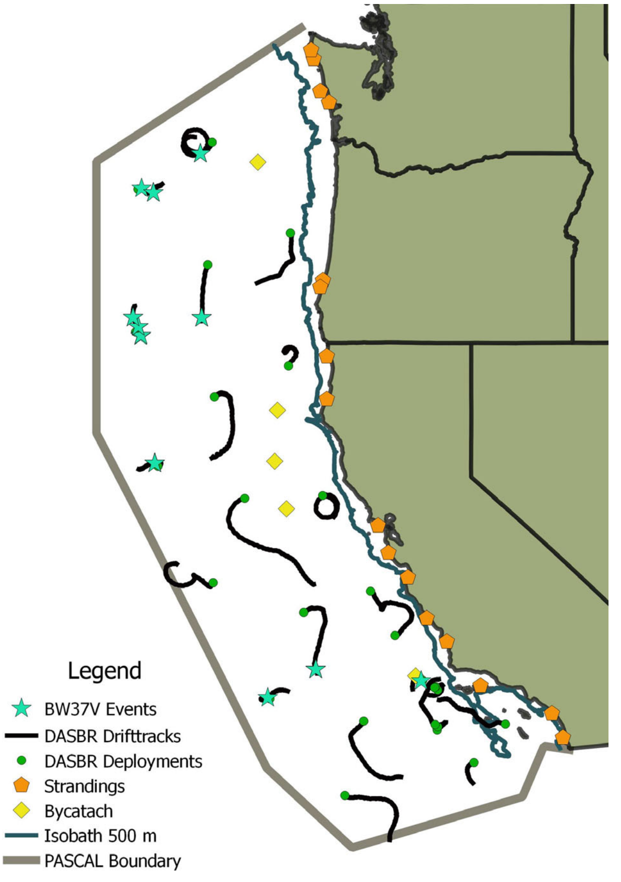

Figure 1. Locations where BW37V pulse types (n = 20) were recorded (blue star) and where Hubb's beaked whale stranding (orange pentagon) and bycatch (yellow diamond) occurred (National Marine Fisheries Service, U.S. Department of Commerce 2017). Drifts of the 29 successful DASBR drifts are illustrated in black, and their deployment locations are plotted as green dots. The boundary of the study area (gray) and the 500 m isobath (navy blue) are also shown.

whale pulse type has a distinct spectral notch/valley between 26 kHz and 27 kHz and has lower frequency peaks at 18 kHz and 22 kHz (Zimmer *et al.* 2005, fig. 5-IV in Baumann-Pickering *et al.* 2013). Currently, only peak frequencies are consistently reported in the literature for beaked whales as spectral valleys are not present on all beaked whale clicks.

From a total of 20 individual events we describe the characteristics and distribution of a distinct FM pulse type. There was a total of 1,369 pulses recorded, but only 238 clicks were at least 20 dB over the noise level at the peak frequency. This pulse type was similar to pulses that have been described for other beaked whales in having a frequency

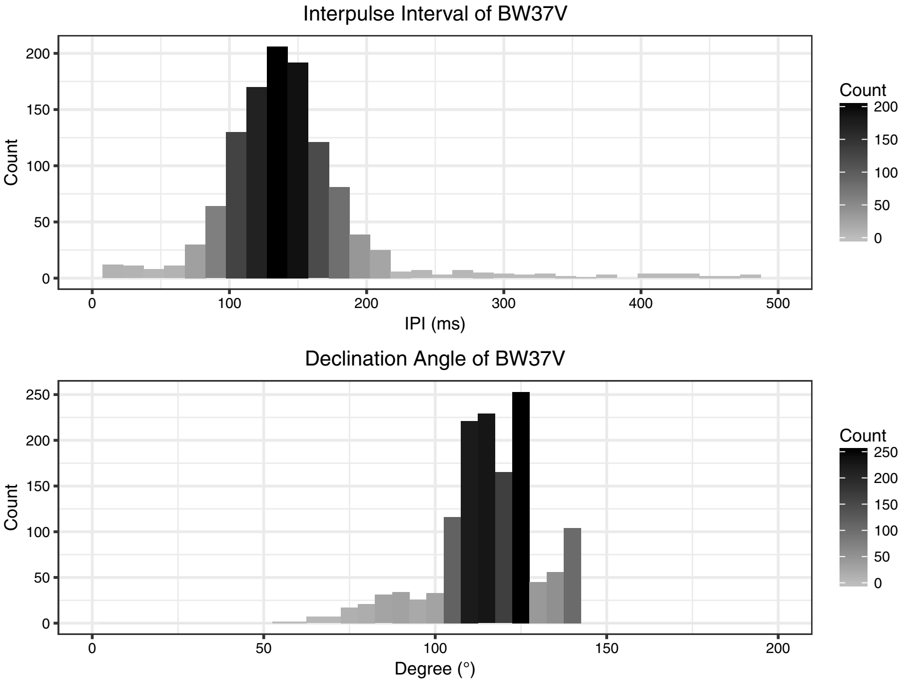

Figure 2. Histograms of the interpulse interval (IPI) and pulse declination angle. All pulse were included to measure the IPI measurements and the pulse declination angle, rather than just the pulses 20 dB above the noise level, as was necessary for the spectral measurements. Outliers (IPI longer than 500 ms) were removed from the final IPI summary.

upsweep and a deep source location. These stereotyped pulses are distinctly bimodal in their frequency distribution, with an upper peak at 47.9 kHz (SD = 7.3), a distinct and sharp lower peak at 36.1 kHz (SD = 5.7), and a stable spectra valley at 37.1 kHz (SD = 2.7) (Table 2). Adapting from previously established nomenclature of beaked whale FM pulses, we called this type BW37V based on its dominant spectral feature, a spectral valley at 37 kHz. To our knowledge, this pulse has not been previously described. All pulses above the 20 dB SNR threshold possessed both peaks and the spectral valley. Typically the upper peak frequency had the greater energy; 153 of 238 pulses had higher energy in the upper peak. Variation in which peak was dominant may be due to variation in the off-axis angle of the receiver rather than variation in the source signals themselves. Most events were comprised of pulse trains, but it is unlikely that we received and recorded full pulse trains for most events since beaked whale pulses are highly directional. The duration (213.1 μs, SD = 87.7) and IPI (146.5 ms, SD = 58.9; Fig. 2) are within the range of other beaked whale pulse types but are shorter than most (Baumann-Pickering *et al.* 2013).

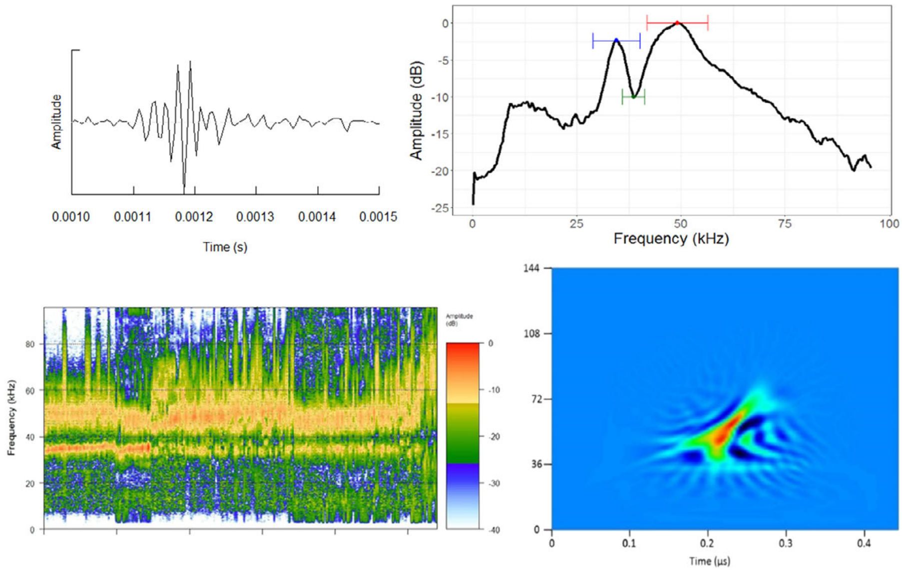

Figure 3. Spectral characteristics of frequency modulated (FM) pulse BW37V. Top left: BW37V waveform. Top right: averaged spectrum of all BW37V pulses 20 dB above the noise floor illustrating three spectral features to identify this pulse type; the lower peak (blue), upper peak (red), and valley (green) frequencies. FFT 512, Sampling rate: 192 kHz. Bottom left: concatenated spectrogram of BW37V pulses (n = 238), ranked by peak frequency. Valley frequency at 37 kHz is clearly seen. FFT: 512, sampling rate: 192 kHz, overlap: 80%. Bottom right: Wigner plot of a BW37V, generated in PAMGuard, illustrates the upsweep within an individual pulse.

The valley frequency exhibited the lower variability of our frequency measures for this new pulse type than the lower and upper peak frequencies (Fig. 3). All three measures are stable within our data, despite the background soundscape, number of individuals present (one or more than one), and declination angle (described further below). The bimodal peak frequencies exhibited different spectral structures. The lower peak is sharp and narrow compared to the upper peak, with a much smaller −3 dB bandwidth (lower: 5.5 kHz, upper: 10.0 kHz) and a smaller standard deviation around their respective peak frequencies (Table 2). The upper peak frequency has a similar spectral structure and peak frequency to several other FM pulses. However, the presence of a highly stable valley and lower peak frequency allow us to reliably identify this pulse type. Therefore, it stands that these characteristics in the BW37V FM pulse are diagnostic.

No other previously described FM pulse types were detected when BW37V was present. All events were detected at an average declination angle of 116° (SD = 15.1, relative to straight up), indicating that they originated from depths below the array (~100 m). The majority of clicks were recorded at an angle of 105° or higher (Fig. 2). When several events were recorded over multiple duty cycles at the same declination angle and likely originated from the same animal/group of animals, average time was 12.4 min (SD = 5.17 min), with a maximum vocal phase of 20 min (mean declination angle: 122°, SD = 7.4°). During drift 11, there were two events of BW37V pulse types separated by 3.73 h, a possible interval between deep dives. This interval is comparable to times documented for other beaked whale species (Tyack *et al.* 2006, Schorr *et al.* 2014). Average drift speed for each DASBR was 169.8 m/h (SD = 63.1 m/h), therefore the theoretical range of a DASBR could capture an interval between deep dives before the unit drifted out of or the animals left the area. However, we cannot use a single DASBR to track the dives of beaked whales (Barlow and Griffiths 2017). Therefore, these times are likely missing data and do not represent comprehensive beaked whale vocal behavior during a dive.

Based on its observed distribution, we hypothesize that BW37V is produced by Hubb's beaked whale. There was only one sighting identified as Hubb's beaked whales in the 1991–2005 California/Oregon/Washington cetacean surveys (off northern Oregon, Hamilton *et al.* 2009) and one "probable" sighting of a Hubb's beaked whale off Big Sur (Carretta *et al.* 2009). Hubb's beaked whale distribution is largely based on the strandings and fisheries bycatch records which have occurred throughout the PASCAL survey study area (Fig. 1). While Stejneger's and Hubb's beaked whales are the only eastern North Pacific *Mesoplodon* beaked whales known to have a cold-water northern range, the distribution of Hubb's beaked whale may be continuous across the North Pacific Ocean towards Japan (MacLeod *et al.* 2005). BW37V were detected most frequently on DASBRs 100 nmi or more offshore, especially in the northern part of the study area. The mean water column depth at our BW37V detections was 3,613 m (SD = 667, range 2,649–4,434 m). Previous studies have focused on seamounts and ridges as the primary habitat for specific beaked whale species (Waring *et al.* 2001, MacLeod and Zuur 2005), and beaked whale acoustic surveys along the US West Coast have concentrated on seamounts and in slope and basin waters off of Southern California (Baumann-Pickering *et al.* 2014). While covering those areas, this study also expanded targeted acoustic survey efforts for beaked whales into the abyssal waters off of the Oregon and Washington coasts. Visual sighting surveys that cover larger regions show that at least some beaked whale species are widely distributed in open ocean waters that are deeper than 3,000 m (Ferguson *et al.* 2006). We believe that the failure of previous studies to recognize the unique BW37V pulse type may simply be because they are rare in areas that have been previously studied and may primarily occur over abyssal plains.

There are other species of odontocete that can dive deep and produce upswept echolocation pulses. Given that the events were recorded at depth and no dolphin clicks were present, it is unlikely a species other than a beaked whale produced these pulses. It is possible that this pulse originates from a previously described species of beaked whale; it could be a variant pulse or have a different behavioral purpose. However, if this were the case, it would be expected that during foraging known pulse types would be recorded. We recorded several events which are consistent with the known forging dive behavior of beaked whales. It is highly unlikely, although possible, that our instruments were out of range for all foraging pulses. There is a higher probability that BW37V is the previously undescribed foraging pulse of a beaked whale. There has been previous recordings of Hubb's beaked whale echolocation, though they were taken with noncomparable methods from two captive juvenile whales which had stranded and were in compromised health (Lynn and Reiss 1992, Marten 2000). As we are specifically looking at foraging pulses from wild animals and it is improbable that beaked whales will emit foraging clicks while stranded, we did not compare these results. Visual confirmation is needed to conclusively attribute this BW37V pulse type to a species. Passive acoustic methods can greatly expand our ability to determine the species distributions of beaked whales, but definitive characterizations are needed for the echolocation pulses of Hubb's beaked whale and many other beaked whale species.

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